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Forced mode-coupling instability in two-dimensional complex plasmas

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It is demonstrated experimentally that the wake-mediated resonant coupling of the in-plane and out-of-plane collective motion in two-dimensional plasma crystals can be induced by applying various types of external forcing. When the forcing is sufficiently strong, it can trigger the mode-coupling instability leading to the melting of the crystalline monolayer. The experimental observations are supported by numerical analysis of the forced collective dynamics of particles with the wake-mediated interactions. The reported results show the universal nature of the wake-mediated mode coupling (also occurring for the “forced” wave modes) and confirm characteristic features of the mode-coupling instability predicted theoretically by Ivlev et al. [Phys. Rev. Lett. **113**, 135002 (2014)].

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Two-dimensional (2D) complex plasmas [1, 2] are often used as model systems to study at the kinetic (particle) level generic phenomena occurring in liquids and crystals [3] such as phase transitions, wave propagation, dislocation dynamics, plastic deformation [4–7]. In a radio-frequency (rf) discharge, microparticles are levitating in the sheath where an inhomogeneous vertical electric field exerts an electric force able to balance the gravity [8, 9], and to ensure stiff confinement of the monolayer. On the other hand, the field-induced ion stream is focussed downstream of each particle and thus creates a perturbed region called the “plasma wake”. Wakes exert an attractive force on the neighbouring particles and make the particle pair interactions non-reciprocal [10–13]. It leads under certain conditions to the formation of an unstable hybrid mode and the melting of the crystalline monolayer [14–17]: In 2D complex plasma crystals, three wave modes can be sustained - two in-plane modes, longitudinal (compressional) and transverse (shear) [18], and one out-of-plane mode [19]. When the crystal is sufficiently dense and/or the vertical confinement is sufficiently weak, the out-of-plane wave mode can cross the in-plane longitudinal mode (usually occurs the border of the first Brillouin zone). Due to the wake forces, this leads to the formation of the hybrid mode which has a positive growth rate, i.e. energy is transferred from the plasma to the crystal and therefore can trigger the mode coupling instability (MCI) [20]. The hybrid mode has clear fingerprints: critical angular dependence, a mixed polarization, distinct thresholds [14], synchronization of the particle motion [21].

In a recent article [15], it was demonstrated that wake-induced mode coupling is possible in both crystalline and liquid complex plasmas. However, in complex plasma liquids, confinement and dust particle density thresholds, which are important features of the MCI in 2D complex plasma crystals, disappear and the instability growth rate

is higher.

In this Letter, we demonstrate experimentally that wake-mediated resonant mode coupling can be induced in a 2D plasma crystal levitating in the sheath of a radio-frequency discharge through an external mechanical excitation mechanism. When the excitation is strong enough, it can lead to the triggering of the MCI and the melting of the crystal layer. Two excitation methods have been investigated: (i) a Mach cone in the crystal, which creates dominantly in-plane longitudinal waves and shows a resonance with the out-of-plane mode, and (ii) a direct mechanical excitation of the crystal which initiates the formation of the hybrid mode and the melting of the crystal. The experimentally measured MCI growth rates in the crystalline and liquid phases and show that the results are in a remarkable agreement with the theoretical prediction [15].

Experiments. The experimental setup used in this study has been extensively described in previous publications [14, 16, 22]. Experiments were performed in a (modified) GEC chamber, in a capacitively coupled rf glow discharge at 13.56 MHz. The argon pressure p was between 0.4 Pa and 1 Pa and the forward rf power P was between 5 W and 20 W. A horizontal monolayer, up to 60 mm in diameter, was formed by levitating melamine-formaldehyde particles with a diameter of $9.19 \pm 0.14 \mu\text{m}$ in the plasma sheath above the lower rf electrode. The dust particle cloud was illuminated by two laser sheets: a vertical one and a horizontal one. The particles were imaged through a window at the top of the chamber by a Photron FASTCAM 1024 PCI camera at a speed of 250 frames per second. The particle horizontal coordinates, x and y , and velocities, v_x and v_y , were then extracted with sub-pixel resolution in each frame by using a standard particle tracking technique [23]. An additional side-view camera (Basler Ace ACA640-100GM or Photron FASTCAM 1024 PCI) was used to check that we were indeed

working with a single layer of particles.

Results: Mach cone experiment. A heavier microparticle was levitating below the crystalline layer. Due to the ion wake fields downstream of each microparticle of the main layer, this particle was accelerated to supersonic velocity and a Mach cone was produced in the crystalline layer [24]. While these cones have a three dimensional structure [22], the launched waves are primarily in-plane. This forced mode was thus used to investigate the induced mode-coupling.

The parameters of the crystal (see table I) were such that the crossing of the in-plane longitudinal mode with the out-of-plane mode was very shallow and only visible at an angle of 0° compared to the lattice main axis [14, 17]. This is well evidenced in Fig. 1(a) where traces of mixed polarization and a hot spot are visible near the border of the first Brillouin zone. The heavy particle moved in a straight line at a given angle compared to the lattice main axis ($\simeq 5^\circ$). Consequently, traces of the Mach cone induced forced mode in the in-plane longitudinal spectra were angle dependent (see Fig. S1 of the supplemental material [25] and the complementary movie [26]). These traces are clearly visible in Figs. 1(a) and (c) as straight lines in the low- k part of the spectra. It should be noted that forced mode branch is clearly detached from the thermal wave modes for normalised wave number $k\Delta \gtrsim 1$ where Δ is the mean interparticle distance. The resonant coupling of the forced mode with the in-plane (lower branch) and the out-of-plane (upper branch) *eigenmodes* is revealed by the *induced* hot spots occurring at the respective crossing points, (Fig. 1). These spots are perfectly aligned with the low- k traces visible in the in-plane spectra. Without the ion wakes such traces would not be possible and are a clear signature of a forced resonance. Obviously, the position of the hot spot is also angle dependent.

TABLE I. Experimental parameters: gas pressure p , particle charge Q , effective screening length λ , interparticle distance Δ . The errors for Q and κ are $\simeq 15\%$ and $\simeq 30\%$, respectively. A complete table can be found in the supplemental material [25].

Experiment	p (Pa)	Q (e)	λ (μm)	Δ (μm)
Mach cone	0.42	20000	733	550
Mechanical excitation	0.94	18230	417	487

Results: Mechanical excitation experiment. A stable 2D crystal (no crossing of the eigenmodes) was levitated above the electrode (see Tab.I for experimental parameters). The in-plane longitudinal fluctuation spectrum of the crystalline layer is shown in Fig. 2(a). No fingerprints of the unstable hybrid mode could be detected and only the eigenmode is present. A kick was then applied to the vacuum chamber. Vibrations were transmitted to

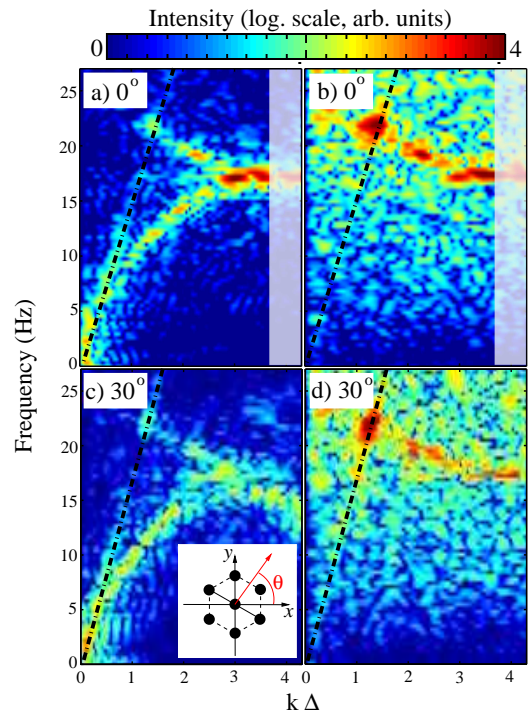


FIG. 1. (Color online) Resonant coupling with the Mach cone. (a,c) and (b,d) are the in-plane longitudinal and out-of-plane fluctuation spectra, respectively, measured in the Mach cone experiment. Only the first Brillouin zone is shown, the beginning of the second zone is shaded in (a,b). The Mach cone primarily generates in-plane collective motion – a *forced mode* (underlined by the dotted-dashed line) which is clearly visible in (a,c). The resonant coupling of the forced mode with the in-plane (lower branch) and the out-of-plane (upper branch) *eigenmodes*, occurring at the respective crossing points, is revealed by the *induced* hot spots. In the most unstable direction $\theta = 0^\circ$ (see the inset), the bright spots close to the border of the first Brillouin zone indicate the formation of the regular hybrid mode (due to the crossing of the eigenmodes) [14, 17].

the crystal and in return the dust particles started to oscillate both vertically and horizontally around their equilibrium positions with amplitudes much higher than the natural thermal oscillations. *Note that the crystal was also oscillating horizontally as a whole, but the respective mean velocity was subtracted before computing mean kinetic energy and current spectra* [25]. In Fig. 2(b), the in-plane longitudinal fluctuation spectrum after the mechanical excitation is plotted. As can be seen, a bright spot emerges at $\simeq 28\text{Hz}$. The resulting second subharmonic oscillations at $\simeq 14\text{Hz}$ induce the resonant coupling with the eigenmode at $k\Delta \simeq 2.3$ (harmonics are commonly observed for large amplitude oscillations in complex plasmas [27, 28]). Another remarkable feature is that the traces of mixed polarization (branches corresponding to the out-of-plane mode in the in-plane spectrum) are visible close to the edge of the first Brillouin zone (yellow spots at $k\Delta \leq 3.63$). This is a fingerprint

of the mode hybridisation and MCI onset.

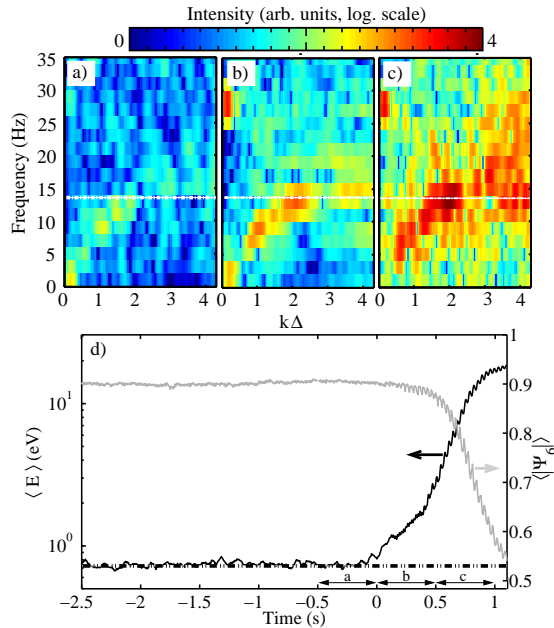


FIG. 2. (Color online) Forced mode-coupling instability, induced by a mechanical excitation. The in-plane longitudinal fluctuation spectra in (a), (b) and (c) are obtained for the time intervals indicated in (d) by the respective arrows. Only the in-plane longitudinal eigenmode is observed before the excitation (a), while after knocking the chamber (at time $t = 0$ s) a bright spot emerges at $\simeq 28$ Hz (c). The resulting second subharmonic oscillations at $\simeq 14$ Hz (horizontal dotted line) induce the resonant coupling with the eigenmode at $k\Delta \simeq 2.3$. The crystal in this experiment is composed of several domains with different orientation; therefore, the shown range of k is limited by the border of the first Brillouin zone at $\theta = 30^\circ$ (see Fig. 1). (d) Evolutions of the (averaged) in-plane kinetic energy and $\langle |\Psi_6| \rangle$ in the experiment. The horizontal dotted-dashed line shows the mean energy level before the excitation. Note the **increase in the exponential energy growth rate and the simultaneous decrease of $\langle |\Psi_6| \rangle$** , occurring at $t \simeq 0.4$ s due to the transition from the crystalline to liquid regime of the mode-coupling instability. For technical reasons (see supplemental material [25]), dynamics of particles with $E_{\text{kin}} \gtrsim 10$ eV cannot be properly followed, which causes artificial saturation of $\langle E \rangle(t)$.

In Fig. 2(d), the evolutions of average kinetic energy of the dust particles is plotted. **In order to demonstrate the evolution of the crystalline symmetry, we also plot the degree of bond-orientational order $\langle |\Psi_6| \rangle$** (see Ref.[16] for the definition of Ψ_6). The kinetic energy started to increase exponentially just after the kick, with a measured growth rate $\gamma_{\text{cryst}} = 1.4 \pm 0.1 \text{ s}^{-1}$. At $t = 0.4$ s, the melting began in the center, reflected by a rapid fall-off of $\langle |\Psi_6| \rangle$, and the growth rate simultaneously increased to $\gamma_{\text{liq}} = 5.8 \pm 0.1 \text{ s}^{-1}$ [29]. This behaviour indicates a transition from the crystalline to the liquid regime of the MCI, as predicted in Ref.[15].

Thus, the mechanical excitation experiment clearly

demonstrates that in slightly undercritical crystals, if a mechanical perturbation is strong enough, hybridisation can be forced and the crystal can undergo sporadic melting (MCI).

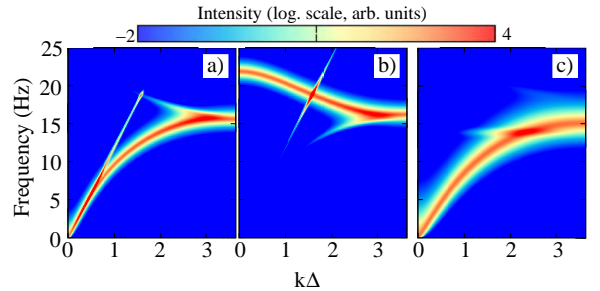


FIG. 3. (Color online) In-plane longitudinal (a) and out-of-plane (b) fluctuation spectra, numerically calculated for the conditions of the Mach cone experiment and representing, respectively, the spectra shown in Figs. 1(a) and (b). (c) In-plane longitudinal fluctuation spectrum, calculated for the mechanical excitation experiment and representing Fig. 2(b). In (a) and (b), the acoustic excitation (straight line) is produced by a test charge moving underneath a crystalline monolayer along the direction $\theta = 0^\circ$, to mimic the Mach cone generated by a projectile particle in the Mach cone experiment; in (c), uncorrelated vertical harmonic forces at the frequency of 14 Hz mimic the second subharmonic oscillations in the mechanical excitation experiment (for details, see supplemental material [25]).

Discussion. In 2D complex plasmas, the wake-mediated coupling between the collective in-plane and out-of-plane motion of particles is driven by non-reciprocity of the interparticle interactions. This is a very generic phenomenon which can occur in any many-particle system where the action-reaction symmetry of the effective interactions is broken due to the presence of a non-equilibrium environment [30]: Examples include optical [31] and diffusiophoretic [32] forces between colloids, the effective interactions under solvent or depletant flow [33–35], shadow forces in 3D complex plasmas [36], etc. It is important to stress that wake-mediated coupling is a pure dynamical phenomenon, and therefore occurs irrespectively of whether the collective particle motion represents a wave eigenmode or is driven externally. This implies that the mode-coupling instability in 2D complex plasmas can also develop if the forced “mode” induces the resonant coupling between the out-of-plane eigenmode and the in-plane eigenmode. For the Mach cone experiment, the resonance is mostly transversal [bright red spot in Figs. 1(b) and (d)]. For the mechanical excitation experiment, the resonance is mostly longitudinal [bright red spot in Fig. 2(b,c)].

Theoretical calculation of the “forced” resonances, presented in Fig. 3 (see also supplemental material [25]), demonstrate a qualitative agreement with the experimental observations. In both experiments we observed the characteristic features peculiar to the “conventional”

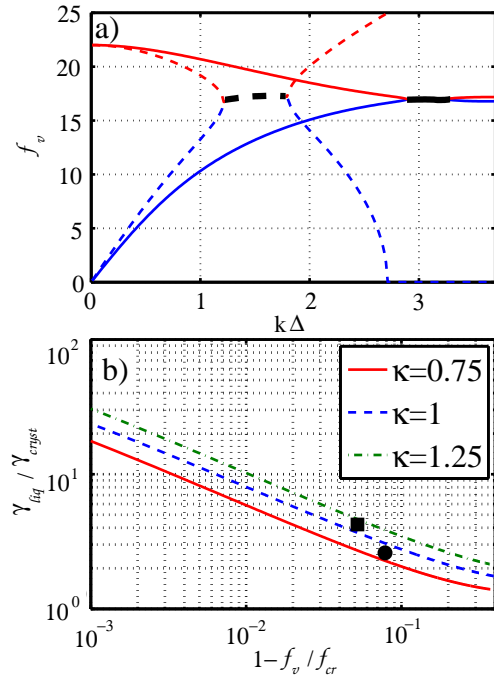


FIG. 4. (Color online) (a) Theoretical dispersion relations for crystalline (solid lines) and liquid (dashed line) layers, showing the unstable hybrid mode (bold black) formed upon the crossing of the in-plane longitudinal (blue) and the out-of-plane (red) eigenmodes. The screening parameter is $\kappa = 1.035$, the vertical resonance frequency is $f_v = 22$ Hz, other parameters correspond to the mechanical excitation experiment. (b) Ratio of the instability growth rates in liquid and crystalline layers, $\gamma_{\text{liq}}/\gamma_{\text{cryst}}$, plotted versus the depth of the mode crossing, $1 - f_v/f_{cr}$, where f_v is the vertical resonance frequency and f_{cr} is the critical (maximum) value of f_v at which the hybrid mode forms in a crystalline layer. The black square and black dot in (b) represent conditions of the mechanical excitation experiment and of the experiment reported in Ref.[16], respectively. The shown results are for the wake charge $q = 0.2|Q|$ and the wake length $\delta = 0.3\lambda$.

mode-coupling instability such as traces of mixed polarisation and hot spots at the resonance frequencies

In a liquid monolayer, the crossing of the out-of-plane and in-plane modes occurs (under the same conditions) at smaller wave numbers, as illustrated in Fig. 4(a). As the MCI develops, the crystal melts and the MCI regime gradually changes from the crystalline to liquid. The hybrid frequency remains the same but the hybrid mode is slowly shifted toward smaller wave numbers. This explains experimental observations of hybrid modes extended toward smaller wave numbers, as reported in Refs.[14, 37, 38] and Fig.2(c).

The second observation concerns the evolution of the MCI growth rate. In this study and in an earlier one [16], it was observed that the MCI growth rate increased significantly during the melting. Ivlev et al. [15] have shown that the MCI growth rate in the fluid γ_{liq} can be larger than the instability growth rate in the crys-

tal γ_{cryst} . In the mechanical excitation experiments, the crystal was stable and the MCI was forced by a strong external excitation. Consequently, a direct quantitative comparison of the crystal and liquid growth rates cannot be performed, but the qualitative trend is as expected. In Fig. 4(b), this effect is illustrated: using the theories developed in Refs.[14, 15, 17], the ratio $\gamma_{\text{liq}}/\gamma_{\text{cryst}}$ has been calculated for different screening parameters κ for given wake parameters (wake charge $q = 0.2|Q|$ and normalized wake distance $\delta = 0.3\lambda$). The horizontal axis represents the depth of the mode crossing in the crystalline state, i.e., the ratio between the critical vertical confinement frequency f_{cr} , which determines when the out-of-plane and in-plane longitudinal modes intersect and form the hybrid mode, and the vertical confinement frequency f_v . When $f_v > f_{cr}$, there is no mode coupling in the crystal and no MCI can develop. When f_v is too small, a monolayer cannot exist any more. $\gamma_{\text{liq}}/\gamma_{\text{cryst}}$ is very large for shallow crossing – this correspond to a marginally unstable state for a crystalline monolayer, while the liquid state is always unstable. When the depth of the crossing increases, both γ_{cryst} and γ_{liq} increase but $\gamma_{\text{liq}}/\gamma_{\text{cryst}}$ decreases. Experimentally, the observed ratios are between 2–4, which corresponds to a crossing of the modes $0.04 \lesssim 1 - f_v/f_{cr} \lesssim 0.08$ [39]

To conclude, we have experimentally demonstrated that wake-mediated resonant mode coupling can be induced in a two-dimensional plasma crystal through an external mechanical excitation. Two excitation mechanisms have been explored: (i) a heavy particle traveling at supersonic velocity under the crystalline layer triggers a Mach cone which induced a forced primarily in-plane mode. (ii) Strong primarily vertical oscillations of the particles induced by an external kick can force the hybridisation of the eigenmodes and trigger the MCI in a principally stable crystal. For both excitation mechanisms, the results are supported by calculations of the forced wake-induced resonance based on the theory of crystalline and liquid MCI[14, 15, 17]. This shows the universal nature of the wake-mediated mode coupling and confirms characteristic features of the mode-coupling instability predicted theoretically by Ivlev et al.[15]. We demonstrate that some previously unexplained features of the MCI-induced melting, such as the increase of the instability growth rate and an extended hybrid mode toward small wave numbers, are associated with the gradual change from crystalline to liquid MCI.

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